

Robust Social Decisions*

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October 14, 2015

Abstract

We propose and operationalize normative principles to guide social decisions when individuals potentially have imprecise and heterogeneous beliefs, in addition to conflicting tastes or interests. To do so we adapt the standard Pareto principle to those preference comparisons that are robust to belief imprecision and characterize social preferences that respect this robust Pareto principle. We similarly characterize a suitable restriction of this principle. The former principle provides stronger guidance when it can be satisfied; when it cannot, the latter always provides minimal guidance.

Keywords. Robust preferences, Pareto dominance, Preference aggregation, Social choice, Uncertainty

JEL Classification. D71, D81

Public policies often yield uncertain outcomes. In order to evaluate the various alternative policies and select an optimal one, policy makers therefore need to rely on some assessment of the probabilities of these outcomes. For some critical issues such as climate change, however, this task is particularly challenging because the uncertainty at hand is not well understood enough to allow a precise assessment of these probabilities.¹

*An earlier version of this paper was circulated under the name “Aggregating Tastes, Beliefs, and Attitudes under Uncertainty”. We thank Marc Fleurbaey, Tzachi Gilboa, Peter Klibanoff, Philippe Mongin, Sujoy Mukerji, Klaus Nehring, Efe Ok, Marcus Pivato, Xiangyu Qu, David Schmeidler, Peter Wakker, and Stéphane Zuber, as well as participants to the D-TEA 2014 meeting, DRI seminar in Paris, workshop in Bielefeld University, and seminars at Columbia University, Koç University, Queen’s University Belfast, ETH-Zurich, University of Oslo, and University of Warwick for useful comments and discussions. Danan thanks support from the Labex MME-DII program (ANR-11-LBX-0023-01). Gajdos thanks support from the A*MIDEX project (ANR-11-IDEX-0001-02) funded by the Investissements d’Avenir program. Hill thanks support from the Investissements d’Avenir program (ANR-11-IDEX-0003/Labex Ecodec/ANR-11-LABX-0047). Tallon thanks support from ANR grant AmGames (ANR-12-FRAL-0008-01) and from the Investissements d’Avenir program (ANR-10-LABX-93).

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¹Besides climate change, Henry (2006) describes two other cases – asbestos and Creutzfeld-Jacob disease – in which public actions had to be (or should have been in the case of asbestos) taken on the basis of “uncertain science” (imprecise scientific knowledge). Manski (2013) discusses how relying on “incredible certitude” can mislead policy analysis and argues for instead acknowledging partial knowledge of individuals’ characteristics.

A major issue is whether there will be significant global warming – for example, of 4°C or more (relative to preindustrial levels) – which would have wide-ranging, and unevenly distributed, consequences on economic activity, human settlement and health around the world (IPCC, 2014). This depends on future concentrations of greenhouse gases (GHG), which themselves depend on climate policy. Both of these dependencies involve considerable uncertainty. On the one hand, climate sensitivity to GHG concentrations is imperfectly understood and cannot as yet be accurately described, even probabilistically, with full precision. Rather, a range of probabilistic models are considered plausible by climate scientists (IPCC, 2013, Section 10.8). On the other hand, the effect of a given policy on GHG concentrations depends, among other factors, on technological evolutions that are highly unpredictable and for which any prediction is essentially subjective (Stern, 2013; Pindyck, 2013). So different actors evaluating a given policy – say the French and British governments evaluating a European climate policy – may rely on different predictions and, hence, end up using different plausible ranges for the probability of global warming reaching 4°C under this policy – say 10% to 50% and 40% to 60%, respectively. In such a situation, how should the policy be evaluated at the European level?

This paper aims at providing guidance for such policy decisions. Situations of this sort involve a “social” decision maker (say the European Commission) who must choose a policy whose outcome is uncertain and affects several “individual” actors (the French and British governments). Individuals may have different utility functions – or have heterogeneous “tastes” – and consider different probabilistic models to be plausible – or have heterogeneous “beliefs”. Moreover, a given individual may also consider more than one model to be plausible – or have an imprecise belief. For such an individual, which of two policies yields the highest expected utility may depend on the model considered. When a policy yields a higher expected utility than another one for all plausible models, we say that the individual has a *robust* preference for the former policy over the latter.²

The Pareto principle is a natural guide for such decisions. We propose a robust version of this principle, requiring that if all individuals robustly prefer a policy to another one then so should the policy maker. We show that this principle prescribes that the policy maker must only rely on probabilistic models that are considered plausible by all individuals. In the example above, this means that in order to guarantee that the implemented policy is robustly Pareto optimal, the European Commission must restrict attention to probabilities of global warming reaching 4°C that belong to both the French and British ranges – between 30% and 40%.

As this example illustrates, the policy maker can respect robust Pareto dominance even when individuals have heterogeneous beliefs, as long as these beliefs are *compatible* – at least one model is unanimously considered plausible. Heterogeneous yet compatible beliefs arise naturally in some contexts.³ But they are ruled out by the standard assumption that all individuals have precise beliefs – each individual considers a single probabilistic model. Under this particular assumption, we recover the well-known result that the standard Pareto principle can only be

²Such preferences were studied axiomatically by Bewley (2002). Note that we use the term “robust” in a different sense than Hansen and Sargent (2001, 2008), although we will establish relationships between the two notions of robustness in Section 4.

³For instance, if individuals’ beliefs originate from partial and distinct but mutually consistent pieces of evidence, or from a common “baseline” probabilistic model that they do not fully trust.

respected when all individuals have identical beliefs (Hylland and Zeckhauser, 1979; Mongin, 1995, 1998).

When individuals have incompatible beliefs – no probabilistic model is unanimously considered plausible – the robust Pareto principle yields no prescription: whatever probabilistic models the policy maker considers plausible, she may end up implementing a robustly Pareto dominated policy. We therefore propose to restrict this principle to policies that only involve outcomes on which individual tastes are homogeneous. We show that this *common-taste* robust Pareto principle prescribes that the policy maker must only rely on probabilistic models that are weighted averages of models considered plausible by at least some individuals. Thus this common-taste restriction provides weaker guidance than the robust Pareto principle when individual beliefs are compatible – in the example above, it prescribes that the European Commission must rely on probabilities between 10% and 60%. On the other hand, it still provides guidance when beliefs are incompatible – it yields the same prescription if the French range were narrowed to between 10% and 30%.

Except in a few special cases, neither the robust Pareto principle nor its common-taste restriction constrain the policy maker to rely on a single probabilistic model. She may do so if she wishes, but she could also rely on a range of models.⁴ Considering a wider range of models results in a larger set of robustly optimal policies and, consequently, the policy maker has more flexibility in selecting the policy to implement within this set. As we demonstrate, the set of robustly optimal policies, however large, can be computed very simply. Moreover, any policy selected within this set corresponds to more or less *cautious* – or conservative – behavior.

Section 1 introduces the formal setup for our analysis. Section 2 contains the main results: characterizations of the robust Pareto principle and its common-taste restriction. Section 3 presents additional results on computing the set of robust optima and making a selection within this set. Section 4 discusses related literature. Proofs are gathered in the Appendix.

1 Setup

1.1 Social decisions

Consider a *society* made of a finite number n of *individuals*. Let S be a finite set of *states of the world* and X be a set of *outcomes*. Society (the social decision maker) has to choose an *act* (a policy) f whose outcome $f(s) \in X$ depends on which state $s \in S$ will occur. Let F denote the set of all acts, that is all functions $f : S \rightarrow X$. We identify an outcome $x \in X$ with the constant act yielding outcome x no matter which state occurs, thus viewing X as a subset of F .

An element of X specifies an outcome for all individuals in society. We assume that X is a convex subset of some Euclidean space. One particular case is the classical setting of [Anscombe and Aumann \(1963\)](#) where X is the set of lotteries over some finite set of prizes. Another one is when X is a convex subset of the set \mathbb{R}^n of monetary allocations or, more generally, of the set \mathbb{R}^{dn} of allocations of a finite number d of commodities. Since X is convex, given any two acts $f, g \in F$ and any coefficient $\lambda \in [0, 1]$ there exists a “mixed” act $\lambda f + (1 - \lambda)g \in F$ yielding

⁴For instance, the common-taste Pareto principle allows the policy maker to consider plausible all models that at least one individual considers plausible, as recently suggested by [Brunnermeier et al. \(2014\)](#).

outcome $\lambda f(s) + (1 - \lambda)g(s)$ in each state $s \in S$.

1.2 Robust SEU preferences

Each individual $i = 1, \dots, n$ has preferences over the acts in F , described by a binary relation \succsim_i on F . That is to say, we write $f \succsim_i g$ when individual i weakly prefers act f to act g . As usual we then write $f \succ_i g$ when this preference is strict and $f \sim_i g$ when it is an indifference. Society also has preferences described by a binary relation \succsim_0 on F . We assume that all these relations are *robust* subjective expected utility (SEU) preference relations in the following sense (we use the generic notation \succsim when the subscript i can be omitted).

Definition 1. A binary relation \succsim on F is a *robust SEU preference relation* if there exist a non-constant, affine utility function $u : X \rightarrow \mathbb{R}$ and a closed, convex set P of probability distributions on S , such that for all $f, g \in F$,

$$f \succsim g \text{ if and only if } E_p(u(f)) \geq E_p(u(g)) \text{ for all } p \in P,$$

where $E_p(u(f)) = \sum_{s \in S} p(s)u(f(s))$ for all $f \in F$ and $p \in P$.

P is interpreted as the set of all probability distributions (probabilistic models) the individual (or society) considers a plausible description of the uncertainty about the state of the world. When P contains a single probability distribution, the agent has standard SEU preferences and prefers the act yielding the highest expected utility under this probability distribution. When P contains multiple probability distributions, the agent only has a robust preference among two acts when one act yields a higher expected utility than the other under all these distributions. If the act yielding the highest expected utility depends on which distribution in P is used, then the individual has no robust preference between the two acts.⁵

Robust SEU preferences were introduced by [Bewley \(2002\)](#). They satisfy all the properties characterizing SEU preferences, except the completeness property. The belief P is uniquely pinned down by the preference relation \succsim , whereas the utility function u is cardinally unique (i.e. unique up to a positive affine transformation).

1.3 Taste heterogeneity

We focus on situations where individuals' tastes or interests, as captured by their respective utility functions, are not perfectly aligned. More precisely, we shall assume that for each individual one can find two constant acts between which this individual is the only one to have a strict preference (all other individuals being indifferent). Say that the profile $(\succsim_i)_{i=1}^n$ of individuals' robust SEU preference relations satisfies *c-diversity* if for all $i = 1, \dots, n$, there exist $x, y \in X$ such that $x \succ_i y$ whereas $x \sim_j y$ for all $j = 1, \dots, n, j \neq i$.⁶

C-diversity is known to be equivalent to the individuals' utility functions being linearly independent (note that this is only possible if X is at least n -dimensional; [Weymark, 1993](#)).

⁵The individual may still come up with an overall preference judgment or reveal a behavioral disposition for one of the two acts; such a preference would simply not be a robust preference. See Section 3.

⁶This property, which is standard in the preference aggregation literature, is often named "independent prospects".

Thus individual tastes cannot be in full agreement, but neither can they be in full disagreement. In fact c -diversity implies that the profile $(\succsim_i)_{i=1}^n$ satisfies the following *c-minimal agreement* property: there exist two constant acts $x, y \in X$ such $x \succ_i y$ for all $i = 1, \dots, n$.

2 Robust Pareto principles

This section contains the main results of the paper. We first state a robust version of the standard Pareto principle and characterize its implications for social preferences. We then consider a weakening of this robust Pareto principle to a particular subset of acts, yielding a more general characterization.

2.1 Robust Pareto dominance

The following is the most straightforward application of the Pareto principle in our context. It simply states that if all individuals robustly prefer f to g , then so should society.

Definition 2. The social robust SEU preference relation \succsim_0 satisfies *robust Pareto dominance* with respect to the profile $(\succsim_i)_{i=1}^n$ of individual robust SEU preference relations if for all acts $f, g \in F$, $f \succsim_0 g$ whenever $f \succsim_i g$ for all $i = 1, \dots, n$.

The following characterization result shows that robust Pareto dominance provides guidance as to which beliefs society might adopt, provided individuals' beliefs are not too heterogeneous.

Theorem 1. Let \succsim_i be a robust SEU preference relation on F with representation (u_i, P_i) for all $i = 0, \dots, n$. Assume $(\succsim_i)_{i=1}^n$ satisfies c -diversity. Then \succsim_0 satisfies robust Pareto dominance with respect to $(\succsim_i)_{i=1}^n$ if and only if there exist a vector of weights $\theta \in \mathbb{R}_+^n$, $\theta \neq 0$, and a constant $\gamma \in \mathbb{R}$ such that

$$u_0 = \sum_{i=1}^n \theta_i u_i + \gamma \quad \text{and} \quad P_0 \subseteq \bigcap_{\substack{i=1 \\ \theta_i > 0}}^n P_i.$$

Theorem 1 provides a way of aggregating individuals' tastes and beliefs. The social utility function is a utilitarian – or linear – aggregation of individuals' utility functions. This simply comes from applying the robust Pareto principle to the constant acts, where it reduces to the standard Pareto principle as beliefs do not matter to evaluate these acts. It is thus a direct extension of [Harsanyi \(1955\)](#)'s aggregation theorem.

More interesting is the way the social belief is constrained by individuals'. When individual beliefs are *compatible* in the sense of having a non-empty intersection, the social belief must lie inside this intersection. Robust Pareto dominance thus yields a strong but intuitive prescription: society must only use probability distributions that all individuals consider plausible. This in particular implies that society's robust preferences are more complete – can rank more alternatives – than any of the individuals'. The condition that the intersection of individuals' beliefs is non-empty is not new in the literature; it appears for instance in [Rigotti and Shannon \(2005\)](#), where it is needed to prove that, absent any aggregate risk, the set of Pareto optima coincide with the full insurance allocations.

If individual beliefs are incompatible – or have an empty intersection – then some individuals have to be “excluded” as it were, i.e. given zero weight in the social utility function. For instance, if all individuals have distinct precise beliefs, then the only way for society to satisfy robust Pareto dominance is that its preferences coincide with a particular individual’s, who then acts as a dictator. More generally, SEU individuals are either given zero weight or are dictators: any individual with SEU preferences and a non-zero weight forces society to have SEU preferences with her prior, in a way forcing her “certitude” on the society.⁷

2.2 Common-taste robust Pareto dominance

When individuals have incompatible beliefs and society does not wish to exclude some of them, the robust Pareto principle yields no prescription for society. To recover some guidance in these situations, we now restrict this principle to acts that are in some sense “consensual”.

Let us start with a situation where our notion of consensus takes a particularly simple form. Consider two constant acts $x, y \in X$ such that $x \succ_i y$ for all $i = 1, \dots, n$ (such acts exist by c-minimal agreement) and two acts $f, g \in F$ that never yield an outcome different from x or y in any state. Such acts are consensual in the sense that all individuals agree state by state on the ranking of their respective outcomes: for all $s \in S$, $f(s)$ is either unanimously “good” – if it is x – or unanimously “bad” – if it is y – and similarly for g . Now if f robustly Pareto dominates g then all individuals, notwithstanding their incompatible and potentially imprecise beliefs, further agree that f is more likely than g to yield the “good” outcome. Put differently, they would continue to unanimously prefer f to g if they agreed to “pool” their beliefs – each of them incorporating the others’ beliefs into her own.

More generally, we say that two acts are “common-taste” acts if all individuals have the same cardinal preferences over their possible outcomes.⁸ Formally, given an act f , let $f(S) = \{f(s) : s \in S\}$ denote the image of f , i.e. the set of all possible outcomes of f . Given a set Y of outcomes, let $\text{conv}(Y)$ denote the convex hull of Y , i.e. the set of all convex combinations (or weighted averages) of outcomes in Y . Two acts f and g are *common-taste acts* if $x \succsim_i y$ is equivalent to $x \succsim_j y$ for all $x, y \in \text{conv}(f(S) \cup g(S))$ and $i, j = 1, \dots, n$. Equivalently, f and g are common-taste acts if all individual utility functions, once restricted to the set of all possible outcomes of these two acts, are identical up to positive affine transformations.

Definition 3. The social robust SEU preference relation \succsim_0 satisfies *common-taste robust Pareto dominance* with respect to the profile $(\succsim_i)_{i=1}^n$ of individual robust SEU preference relations if for all common-taste acts $f, g \in F$, $f \succsim_0 g$ whenever $f \succsim_i g$ for all $i = 1, \dots, n$.

Theorem 2. Let \succsim_i be a robust SEU preference relation on F with representation (u_i, P_i) for all $i = 0, \dots, n$. Assume $(\succsim_i)_{i=1}^n$ satisfies c-minimal agreement. Then \succsim_0 satisfies common-taste robust Pareto dominance with respect to $(\succsim_i)_{i=1}^n$ if and only if there exist a vector of weights

⁷A similar pattern was experimentally observed by Baillon et al. (2012).

⁸In the two-outcome situations discussed above there is no distinction between ordinal and cardinal preferences. This is no longer true with more than two outcomes and requiring identical cardinal preferences turns out to provide the relevant notion of common-taste acts for our purposes.

$\theta \in \mathbb{R}_+^n$, $\theta \neq 0$, and a constant $\gamma \in \mathbb{R}$ such that

$$u_0 = \sum_{i=1}^n \theta_i u_i + \gamma, \quad \text{and} \quad P_0 \subseteq \text{conv} \left(\bigcup_{i=1}^n P_i \right).$$

Thus common-taste robust Pareto dominance allows aggregation of robust preferences even with incompatible beliefs. As in Theorem 1, society can have SEU preferences even if all individuals have imprecise beliefs. The opposite case is now also possible: society can have imprecise beliefs even if all individuals have SEU preferences, in which case social belief imprecision results from individual belief heterogeneity. Thus, although more permissive in the way society's beliefs could be related to individuals' compared with Theorem 1, this result always provides guidance to construct these beliefs.

Remark 1. We would obtain the same characterization if we strengthened the common-taste Pareto principle by focusing on the “involved” individuals, in the spirit of Gilboa et al. (2014): individual i is involved in the comparison between f and g if $f(s) \succsim_i g(s)$ for some $s \in S$. That is, we would now say, more generally, that f and g are common-taste acts if $x \succsim_i y$ is equivalent to $x \succsim_j y$ for all $x, y \in \text{conv}(f(S) \cup g(S))$ and all individuals i, j that are involved in f and g . Equivalently, f and g are common-taste acts if all individual utility functions, once restricted to the set of all possible outcomes of these two acts, are either identical up to positive affine transformations or constant.

Remark 2. Unlike Theorem 1, Theorem 2 does not require individual preferences to satisfy c -diversity but only c -minimal agreement. It is therefore applicable to the particular case where all individuals have identical tastes.

3 Social optima and social choice

This section turns to the problem of choosing a socially optimal act among a given set of feasible acts. We provide results helping society to compute the set of optimal acts and make a further selection among them.

A feasible act is optimal if no other feasible act is strictly preferred to it. When society has a precise belief p_0 , the socially optimal acts are thus simply those that maximize expected social utility under p_0 . When society has an imprecise belief P_0 , on the other hand, the set of socially optimal acts cannot be computed by maximizing a single function, reflecting the incompleteness of the social robust preference relation. However, we show that maximizing expected social utility under each “interior” distribution in P_0 separately always yields a lower bound for – a subset of – this set. Moreover, when the feasible set is convex, doing so under all “boundary” distributions in P_0 as well yields an upper bound for this set. Finally, when the feasible set is polyhedral – determined by a finite system of weak linear inequalities – the lower bound is actually an exact characterization of the set of social optima.⁹

Proposition 1. Let \succsim be a robust SEU preference relation with representation (u, P) and G be a subset of F . Then any act maximizing $E_p(u(f))$ in G for some relatively interior $p \in P$

⁹Aumann (1962, 1964) and Evren (2014) prove similar “scalarization” results in different settings.

is optimal for \succsim in G . Conversely, if G is convex then any optimal act for \succsim in G maximizes $E_p(u(f))$ in G for some $p \in P$, and if G is polyhedral then any optimal act for \succsim in G maximizes $E_p(u(f))$ in G for some relatively interior $p \in P$.¹⁰

Once the socially optimal acts are identified, society may wish to select among them by “completing” the robust social ranking in a consistent way rather than picking an act arbitrarily. Formally, we say that a binary relation \succsim' on F is a *completion* of a robust preference relation \succsim on F if (i) \succsim' is complete, (ii) $f \succsim g$ implies $f \succsim' g$ for all $f, g \in F$, and (iii) $x \succ y$ implies $x \succ' y$ for all $x, y \in X$. As we next show, virtually any consistent completion can be interpreted as evaluating the different acts with varying degrees of “caution” in the following sense.

Definition 4. A binary relation \succsim' on F is a *variable caution choice rule* for a robust SEU preference relation \succsim on F with representation (u, P) if there exists a function $\alpha : F \rightarrow [0, 1]$ such that for all $f, g \in F$,

$$f \succsim' g \text{ if and only if } V(f) \geq V(g),$$

where $V(f) = \alpha(f) \min_{p \in P} E_p(u(f)) + (1 - \alpha(f)) \max_{p \in P} E_p(u(f))$ for all $f \in F$.

The coefficient $\alpha(f)$ is interpreted as the degree of caution with which act f is evaluated. It is unique whenever the minimal and maximal expected utilities of f do not coincide (otherwise it is irrelevant), and independent of (u, P) . The most cautious rule corresponds to $\alpha(f) = 1$ for all $f \in F$ (Gilboa et al., 2010). It is akin to the precautionary principle, each act being evaluated by its minimal expected utility. The least cautious rule corresponds to $\alpha(f) = 0$ for all $f \in F$. More generally, taking α constant corresponds to the Hurwicz (1951) “optimism-pessimism” criterion. Letting α vary with the act allows for more general rules. For instance, choosing a distribution $p' \in P$ and taking $\alpha(f) = \frac{\max_{p \in P} E_p(u(f)) - E_{p'}(u(f))}{\max_{p \in P} E_p(u(f)) - \min_{p \in P} E_p(u(f))}$ corresponds to a SEU rule.

Proposition 2. If a binary relation \succsim' on F is a transitive, c -Archimedean completion of a robust SEU preference relation \succsim on F then it is a variable caution choice rule for \succsim .¹¹

Transitivity requires the completion to rank acts in a consistent way. The c -Archimedean property, on the other hand, is a mild continuity requirement. When these two requirements are met, selecting among socially optimal acts thus amounts to adopt a more or less cautious attitude towards social belief imprecision. The degree of social caution may depend on the act under consideration.

Remark 3. The converse of Proposition 2 does not hold: some variable caution choice rules – or α functions – reverse some robust SEU rankings and hence are not completions of it. The converse holds, however, for all the particular cases discussed above. It holds, more generally, if the definition of a variable caution choice rule is strengthened to further require that $V(f) \geq V(g)$ whenever $E_p(u(f)) \geq E_p(u(g))$ for all $p \in P$.

¹⁰A distribution $p \in P$ is *relatively interior* if for all distribution $q \in P$, there exist a distribution $r \in P$ and a coefficient $\lambda \in (0, 1)$ such that $p = \lambda q + (1 - \lambda)r$.

¹¹A binary relation \succsim' on F is *c-Archimedean* if the sets $\{\lambda \in [0, 1] : \lambda x + (1 - \lambda)y \succsim' f\}$ and $\{\mu \in [0, 1] : f \succsim' \mu x + (1 - \mu)y\}$ are closed for all $f \in F$ and $x, y \in X$.

Remark 4. Our definition of a variable caution choice rule is identical to [Cerreia-Vioglio et al. \(2011\)](#)’s definition of a “generalized Hurwicz representation”, except that they require \succsim to be derived from \succsim' in a specific way whereas we more generally allow \succsim to be any robust SEU preference relation admitting \succsim' as completion. [Cerreia-Vioglio et al. \(2011\)](#) show that any “monotonic Bernoullian Archimedean” (MBA) preference relation admits such a representation.¹² Any MBA preference relation is a transitive, c-Archimedean completion of some robust SEU preference relation, but the converse is not true as MBA preferences satisfy a stronger Archimedean property.

4 Discussion and related literature

In this section, we further discuss the relationship between our main results and the existing literature on social decisions. Whereas most of the literature assumes SEU preferences, a recent strand of papers considers ambiguity – or nonexpected utility – preferences.

4.1 Social decisions with SEU preferences

When individuals and society have SEU preferences and individual tastes are heterogeneous, respecting Pareto dominance is impossible unless all individuals (with non-zero weight) have identical beliefs ([Hylland and Zeckhauser, 1979](#); [Mongin, 1995, 1998, 2014](#)). [Theorem 1](#) generalizes this result to robust SEU preferences. This generalization is partly a possibility result: the robust Pareto principle can accommodate simultaneous heterogeneity in tastes and beliefs, as long as beliefs remain compatible. In the particular case where all individuals have SEU preferences, it also yields the following corollary, showing that the assumption that society has a precise belief is not necessary for the impossibility result as it is in fact implied by the Pareto principle.

Corollary 1. Let \succsim_0 be a robust SEU preference relation on F and \succsim_i be a SEU preference relation on F for all $i = 1, \dots, n$. Assume $(\succsim_i)_{i=1}^n$ satisfies c-diversity. If \succsim_0 satisfies robust Pareto dominance with respect to $(\succsim_i)_{i=1}^n$ then \succsim_0 is a SEU preference relation.

[Gilboa et al. \(2004\)](#) restrict the Pareto principle to “common-belief” acts, i.e. acts whose outcome only depends on events to which all individuals assign the same probability. In the setting of [Savage \(1954\)](#), they show that this restriction allows aggregation of SEU preferences with heterogeneous tastes and beliefs, and requires the social belief to be a weighted average of the individuals’. In an Anscombe-Aumann setting, [Qu \(2015\)](#) obtains the same characterization by restricting the Pareto principle to common-taste acts. These two restrictions have the same flavor of allowing society to ignore “spurious” unanimities (individuals agree for opposite reasons), which are the source of the impossibility. The Savage setting features a rich set of states, making the common-belief restriction stronger, whereas the Anscombe-Aumann setting features a rich set of outcomes, making the common-taste restriction stronger. [Theorem 2](#) generalizes [Qu \(2015\)](#) result to robust SEU preferences.¹³

¹²The MBA class includes virtually all popular ambiguity models, such as maxmin expected utility (MEU; [Gilboa and Schmeidler, 1989](#)), Choquet expected utility (CEU; [Schmeidler, 1989](#)), smooth ambiguity ([Klibanoff et al., 2005](#)), variational ([Maccheroni et al., 2006](#)), and multiplier ([Hansen and Sargent, 2001](#)) preferences.

¹³Note that [Qu \(2015\)](#) also defines common-taste acts more narrowly as those yielding only convex combinations of two exogeneously fixed outcomes between which individuals have a unanimous strict preference. Our more

Gilboa et al. (2014) say that an act f *no-betting Pareto dominates* an act g if f Pareto dominates g and there exists a probability distribution p on S such that $E_p(u_i(f)) \geq E_p(u_i(g))$ for all involved individual i (their definition requires strict inequality, but this weak version is more directly comparable to ours). Their definition can be generalized to robust SEU preferences by requiring robust Pareto dominance instead of Pareto dominance. Gayer et al. (2014) say that an act f *unanimity Pareto dominates* an act g if $E_{p_j}(u_i(f)) \geq E_{p_j}(u_i(g))$ for all involved individuals i, j . Their definition (which again requires strict inequality) can also be generalized to robust SEU preferences by requiring that $E_{p_j}(u_i(f)) \geq E_{p_j}(u_i(g))$ for all individuals i, j and all probability distribution $p_j \in P_j$. Common-taste robust Pareto dominance then implies unanimity robust Pareto dominance, which itself implies no-betting robust Pareto dominance and in turn robust Pareto dominance. Moreover, the last two are equivalent when individual beliefs are compatible. Finally, Theorem 2 implies that it is equivalent for a social robust SEU preference relation to respect either one of the first two when c-minimal agreement holds.

Brunnermeier et al. (2014) propose a *belief neutral social welfare criterion* that essentially consists in a social robust SEU ranking whose belief is the convex hull of the individuals'. This corresponds to the particular case of Theorem 2 where individuals have SEU preferences and society has the least complete robust SEU preferences satisfying common-taste robust Pareto dominance. The common-taste robust Pareto principle thus provides foundations for a generalization of their criterion allowing, on the one hand, for more precise social beliefs – or more complete social preferences – and, on the other hand, for imprecise individual beliefs.

4.2 Social decisions with ambiguity preferences

When individuals and society have ambiguity preferences and individual tastes are heterogeneous, respecting Pareto dominance becomes impossible even when all individuals have identical beliefs. This has been shown in various settings covering in particular the class of MBA preferences (Gajdos et al., 2008; Herzberg, 2013; Chambers and Hayashi, 2014; Mongin and Pivato, 2015; Zuber, 2015). In contrast, Theorems 1 and 2 show that robust SEU preferences allow the aggregation of imprecise beliefs.

Moreover, our results can be used to obtain positive aggregation results for ambiguity preferences as well. Indeed, an ambiguity preference relation naturally induces an “unambiguous preference” relation, capturing the part of the preference ranking that is not affected by the ambiguity the individual perceives (Ghirardato et al., 2004; Nehring, 2007; Klibanoff et al., 2014). For an MBA preference relation \succsim , this unambiguous preference relation \succsim^* is a robust SEU preference relation and \succsim is a variable caution choice rule for its unambiguous part \succsim^* . \succsim can therefore be represented by a triple (u, P, α) where (u, P) is as in Definition 1 and α is an in Definition 4.¹⁴ The function α is then interpreted as reflecting the individual’s attitude towards the ambiguity she perceives.

We may therefore restrict the Pareto principle as follows: say that the social preference rela-

general definition yields the same characterization while retaining a stronger Pareto principle. See also Billot and Vergopoulos (2014) for a different resolution of the impossibility through an extension of the state space.

¹⁴Note that in this approach \succsim is the only primitive relation whereas \succsim^* is revealed by \succsim . Note also that the definition of \succsim^* – or, equivalently, of P – by Ghirardato et al. (2004) and Nehring (2007) does not necessarily coincide with that by Klibanoff et al. (2014), the former being generally more complete.

tion \succsim_0 satisfies *unambiguous Pareto dominance* with respect to the profile $(\succsim_i)_{i=1}^n$ of individual preference relations if the social unambiguous preference relation \succsim_0^* satisfies robust Pareto dominance with respect to the profile $(\succsim_i^*)_{i=1}^n$ of individual unambiguous preference relations. This principle, and its restriction to common-taste acts, are then characterized as in Theorems 1 and 2, respectively. Note that these characterizations do not involve the functions α_i and thus relate the individuals' and society's beliefs independently of their ambiguity attitudes. We explicitly state the latter result.

Corollary 2. Let \succsim_i be a MBA preference relation on F with representation (u_i, P_i, α_i) for all $i = 0, \dots, n$. Assume $(\succsim_i)_{i=1}^n$ satisfies c-minimal agreement. Then \succsim_0 satisfies common-taste unambiguous Pareto dominance with respect to $(\succsim_i)_{i=1}^n$ if and only if there exist a vector of weights $\theta \in \mathbb{R}_+^n$, $\theta \neq 0$, and a constant $\gamma \in \mathbb{R}$ such that

$$u_0 = \sum_{i=1}^n \theta_i u_i + \gamma \quad \text{and} \quad P_0 \subseteq \text{conv} \left(\bigcup_{i=1}^n P_i \right).$$

Several particular specifications of this general characterization have been studied within various subclasses of MBA preferences. Crès et al. (2011), Nascimento (2012), Hill (2013), and Gajdos and Vergnaud (2013) assume that individuals have identical tastes. Allowing for taste heterogeneity, Qu (2015) characterizes a strengthening of common-taste Pareto dominance within the MEU and CEU classes. Alon and Gayer (2015) assume that individuals have SEU preferences whereas society has MEU preferences and characterize unanimity Pareto dominance.

Appendix: proofs

Given a utility function $u : X \rightarrow \mathbb{R}$ and a probability distribution p on S , define the “state-dependent utility” function $w_{u,p} : X \times S \rightarrow \mathbb{R}$ by $w_{u,p}(x, s) = p(s)u(x)$. Given a set P of probability distributions on S , let $W_{u,P} = \{w_{u,p} : p \in P\}$. Let

$$C = \{c \in \mathbb{R}^{X \times S} : c(x, s) = c(y, s) \text{ for all } x, y \in X \text{ and } s \in S\}$$

denote the set of “state-dependent constant” functions. Let $\text{cone}(\cdot)$ denote conic hull.

Lemma 1. Let \succsim_i be a robust SEU preference relation on F with representation (u_i, P_i) for all $i = 0, \dots, n$. Assume $(\succsim_i)_{i=1}^n$ satisfies c-minimal agreement. Then \succsim_0 satisfies robust Pareto dominance with respect to $(\succsim_i)_{i=1}^n$ if and only if

$$W_{u_0, P_0} \subseteq \sum_{i=1}^n \text{cone}(W_{u_i, P_i}) + C. \quad (1)$$

Proof. X has a finite affine basis \hat{X} since it is a subset of a Euclidean space. Given a state-dependent utility function $w : X \times S \rightarrow \mathbb{R}$, denote by \hat{w} its restriction to $\hat{X} \times S$. Given a set W of such functions, denote by \hat{W} the set of corresponding restrictions. Then (1) is equivalent to

$$\hat{W}_{u_0, P_0} \subseteq \sum_{i=1}^n \text{cone}(\hat{W}_{u_i, P_i}) + \hat{C}. \quad (2)$$

It follows from a straightforward generalization of [Danan et al. \(2015\)](#)’s aggregation theorem that \succsim_0 satisfies robust Pareto dominance with respect to $(\succsim_i)_{i=1}^n$ if and only if W_{u_0, P_0} is included in the closure of the right hand side of (2). Hence it suffices to prove that this right hand side is closed. We first show that $\text{cone}(\hat{W}_{u_i, P_i}) + \hat{C}$ is a closed, convex cone for all $i = 1, \dots, n$. That it is a convex cone is easily checked. For closedness, note that $0 \notin \hat{W}_{u_i, P_i}$ since u_i is non-constant and, hence, $\text{cone}(\hat{W}_{u_i, P_i})$ is closed since \hat{W}_{u_i, P_i} is compact and convex ([Rockafellar, 1970](#), Corollary 9.6.1). Moreover, $\text{cone}(\hat{W}_{u_i, P_i}) \cap \hat{C} = \{0\}$ and, hence, $\text{cone}(\hat{W}_{u_i, P_i}) + \hat{C}$ is closed as well ([Rockafellar, 1970](#), Corollary 9.1.3).

It remains to show that the sum of these closed, convex cones is itself closed. As explained in [Danan et al. \(2015\)](#), this will be the case if there exist two acts $f, g \in F$ such that, for all $i = 1, \dots, n$ and all $g_i \in F$ such that $f \succsim_i g_i$, there exist $g'_i \in F$ and $\lambda_i \in (0, 1)$ such that $f \succsim_i g'_i$ and $g = \lambda_i g_i + (1 - \lambda_i)g'_i$. To establish this property, recall that by c-minimal agreement, there exist $x, y \in X$ such that $x \succ_i y$ for all $i = 1, \dots, n$. Hence, for all $i = 1, \dots, n$, there exists an open neighborhood Y_i of y in X such that $x \succ_i y'$ for all $y' \in Y_i$. Let $Y = \bigcap_{i=1}^n Y_i$. Then Y is open and $x \succ_i y'$ for all $y' \in Y$ and all $i = 1, \dots, n$. Fix an outcome $z \in Y$, an individual $i = 1, \dots, n$, an act $g_i \in F$ such that $x \succsim_i g_i$, and a coefficient $\lambda \in (0, 1)$. Let $g'_i = \frac{1}{1-\lambda}z - \frac{\lambda}{1-\lambda}g_i$, so that $z = \lambda g_i + (1 - \lambda)g'_i$. Since S is finite, there exists $\lambda \in (0, 1)$ small enough so that $g'_i \in Y^S \subset F$ and, hence, $x \succ_i g'_i(s)$ for all $s \in S$. It follows that $x \succsim_i g'_i$. \square

Proof of Theorem 1. The “if” part is easily checked. For the “only if” part, assume \succsim_0 satisfies robust Pareto dominance with respect to $(\succsim_i)_{i=1}^n$. Restricting attention to the constant

acts, robust Pareto dominance reduces to standard Pareto dominance. We can therefore apply [Harsanyi \(1955\)](#)'s aggregation theorem (for a rigorous proof in our setting, see [de Meyer and Mongin, 1995](#)) to obtain $\theta \in \mathbb{R}_+^n$ and $\gamma \in \mathbb{R}$ such that $u_0 = \sum_{i=1}^n \theta_i u_i + \gamma$. θ and γ are unique by c-diversity. Moreover, $\theta \neq 0$ since u_0 is non-constant.

It remains to prove that for all $p_0 \in P_0$ and all $i = 1, \dots, n$ such that $\theta_i > 0$, $p_0 \in P_i$. To this end, note that by [Lemma 1](#), there exist $(p_i)_{i=1}^n \in \prod_{i=1}^n P_i$, $\theta' \in \mathbb{R}_+^n$, and $c' \in C$ such that

$$w_{u_0, p_0} = \sum_{i=1}^n \theta'_i w_{u_i, p_i} + c'.$$

It follows that

$$p_0(s)u_0(x) = \sum_{i=1}^n \theta'_i p_i(s)u_i(x) + c'(s) \quad (3)$$

for all $s \in S$ and $x \in X$, where $c'(s)$ stands for $c'(x, s)$ since the latter is independent of x . Summing over S yields

$$u_0(x) = \sum_{i=1}^n \theta'_i u_i(x) + \sum_{s \in S} c'(s)$$

for all $x \in X$, so that $\theta = \theta'$ and $\gamma = \sum_{s \in S} c'(s)$. Hence [\(3\)](#) implies that

$$p_0(s)(u_0(x) - u_0(y)) = \sum_{i=1}^n \theta_i p_i(s)(u_i(x) - u_i(y))$$

and, hence, that

$$\sum_{i=1}^n \theta_i (p_0(s) - p_i(s))(u_i(x) - u_i(y)) = 0 \quad (4)$$

for all $s \in S$ and $x, y \in X$. Fix an individual i such that $\theta_i > 0$. By c-diversity, there exist $x, y \in X$ such that $u_i(x) > u_i(y)$ whereas $u_j(x) = u_j(y)$ for all $j = 1, \dots, n$, $j \neq i$. By [\(4\)](#), it follows that $p_0(s) = p_i(s)$ for all $s \in S$, so that $p_0 = p_i \in P_i$. \square

Proof of Theorem 2. The ‘‘if’’ part is easily checked. For the ‘‘only if’’ part, assume \succsim_0 satisfies common-taste robust Pareto dominance with respect to $(\succsim_i)_{i=1}^n$. As in the proof of [Theorem 1](#), we first restrict attention to the constant acts to obtain $\theta \in \mathbb{R}_+^n$, $\theta \neq 0$, and $\gamma \in \mathbb{R}$ such that $u_0 = \sum_{i=1}^n \theta_i u_i + \gamma$.

It remains to prove that for all $p_0 \in P_0$, there exist $(p_i)_{i=1}^n \in \prod_{i=1}^n P_i$ and $\lambda \in \Delta^n$ such that $p_0 = \sum_{i=1}^n \lambda_i p_i$. By c-minimal agreement, there exist $x, y \in X$ such that $x \succ_i y$ for all $i = 1, \dots, n$. Hence all acts in $\text{conv}(\{x, y\})^S$ are common-taste acts. It follows that $x \succ_0 y$, so that individual and social preferences all agree on $\text{conv}(\{x, y\})$. Hence for all $i = 1, \dots, n$, there exist $a_i \in \mathbb{R}_+$, $a_i > 0$, and $b_i \in \mathbb{R}$ such that

$$u_i(z) = a_i u_0(z) + b_i \quad (5)$$

for all $z \in \text{conv}(\{x, y\})$. We can therefore use the common-taste robust Pareto principle to show, as in the proof of Theorem 1, that for all $p_0 \in P_0$, there exist $(p_i)_{i=1}^n \in \prod_{i=1}^n P_i$, $\theta' \in \mathbb{R}_+^n$, and $c' \in C$ such that

$$p_0(s)u_0(z) = \sum_{i=1}^n \theta'_i p_i(s) u_i(z) + c'(s) \quad (6)$$

for all $s \in S$ and $z \in \text{conv}(\{x, y\})$. Summing over S and using (5) yields

$$u_0(z) = \sum_{i=1}^n \theta'_i u_i(z) + \sum_{s \in S} c'(s) = \sum_{i=1}^n \theta'_i a_i u_0(z) + \sum_{i=1}^n \theta'_i b_i + \sum_{s \in S} c'(s)$$

for all $z \in \text{conv}(\{x, y\})$, so that $\sum_{i=1}^n \theta'_i a_i = 1$ and $\sum_{i=1}^n \theta'_i b_i = -\sum_{s \in S} c'(s)$ since u_0 is non-constant on $\text{conv}(\{x, y\})$. Hence (6) implies that

$$p_0(s)(u_0(x) - u_0(y)) = \sum_{i=1}^n \theta'_i p_i(s)(u_i(x) - u_i(y)) = \sum_{i=1}^n \theta'_i p_i(s) a_i (u_0(x) - u_0(y))$$

and, hence, that

$$p_0(s) = \sum_{i=1}^n \theta'_i a_i p_i(s)$$

for all $s \in S$, so that $p_0 = \sum_{i=1}^n \theta'_i a_i p_i$. Let $\lambda = (\theta'_i a_i)_{i=1}^n \in \mathbb{R}^n$. Since $\theta'_i \geq 0$ and $a_i > 0$ for all $i = 1, \dots, n$ and $\sum_{i=1}^n \theta'_i a_i = 1$, we have $\lambda \in \Delta^n$. \square

Proof of Proposition 1. First, let G be any subset of X and let $g \in \arg \max_{f \in G} E_p(u(f))$ for some relatively interior $p \in P$. We show that g is optimal for \succsim in G . Suppose not, i.e. there exists $f \in G$ such that $f \succ g$. It must then be that $E_p(u(f)) = E_p(u(g))$ whereas $E_q(u(f)) > E_q(u(g))$ for some $q \in P$. Moreover, since p is relatively interior in P , there exist $r \in P$ and $\lambda \in (0, 1)$ such that $p = \lambda q + (1 - \lambda)r$, i.e. $r = \frac{1}{1-\lambda}p - \frac{\lambda}{1-\lambda}q$. It follows that

$$E_r(u(f)) = \frac{1}{1-\lambda} E_p(u(f)) - \frac{\lambda}{1-\lambda} E_q(u(f)) < \frac{1}{1-\lambda} E_p(u(g)) - \frac{\lambda}{1-\lambda} E_q(u(g)) = E_r(u(g)),$$

contradicting $f \succ g$.

Next, assume G is convex and $g \in G$ is optimal for \succsim in G , i.e. there exists no $f \in G$ such that $f \succ g$. We show that $g \in \arg \max_{f \in G} E_p(u(f))$ for some $p \in P$. Let

$$A = \{v \in \mathbb{R}^S : \text{there exists } f \in G \text{ such that } v(s) = u(f(s)) - u(g(s)) \text{ for all } s \in S\},$$

$$B = \{v \in \mathbb{R}^S : E_q(v) > 0 \text{ for all } q \in P\}.$$

Then A is convex since G is convex and u is affine, and B is a convex cone whose dual cone is $\text{cone}(P)$. Moreover, since g is optimal for \succsim in G , A and B must be disjoint by Definition 1. Hence by a separation argument (Rockafellar, 1970, Theorem 11.3), there exists $p \in \mathbb{R}^S$, $p \neq 0$,

such that

$$\sum_{s \in S} p(s)b(s) \geq 0 \geq \sum_{s \in S} p(s)a(s).$$

for all $a \in A$ and $b \in B$. The former inequality implies that $p \in \text{cone}(P)$, so we can assume without loss of generality that $p \in P$. The latter inequality then implies that $E_p(u(g)) \geq E_p(u(f))$ for all $f \in G$.

Finally, assume G is polyhedral and $g \in G$ is optimal for \succsim in G , i.e. there exists no $f \in G$ such that $f \succ g$. We show that $g \in \arg \max_{f \in G} E_p(u(f))$ for some relatively interior $p \in P$. Define A as above and let

$$B' = \{v \in \mathbb{R}^S : E_q(v) \geq 0 \text{ for all } q \in P\}.$$

Then A is polyhedral since G is polyhedral and u is affine, and B' is a closed, convex cone whose dual cone is $\text{cone}(P)$. Since A is polyhedral and $0 \in A$, $\text{cone}(A)$ is a closed, convex cone (Rockafellar, 1970, Corollary 19.7.1). We also have $B' = B'_1 + B'_2$ where B'_1 is the lineality space of B' and B'_2 is a pointed, closed, convex cone orthogonal to B'_1 . Since B'_2 is pointed, there exists a compact, convex set $D \subset B'_2$, $0 \notin D$, such that $\text{cone}(D) = B'_2$ and, hence, $\text{cone}(B'_1 + D) = B'$. Moreover, since g is optimal for \succsim in G , we have $A \cap B' \subseteq B'_1$ by Definition 1 and, hence, A and $B'_1 + D$ must be disjoint since $0 \notin D$. Hence by a separation argument (Rockafellar, 1970, Corollary 20.3.1), there exists $q \in \mathbb{R}^S$, $q \neq 0$, and $\varepsilon \in \mathbb{R}$ such that

$$\sum_{s \in S} q(s)b(s) > \varepsilon \geq 0 \geq \sum_{s \in S} q(s)a(s).$$

for all $a \in A$ and $b \in B'_1 + D$. It follows that there exists an open neighborhood Q of q such that, for all $r \in Q$,

$$\sum_{s \in S} r(s)b(s) \geq 0 \geq \sum_{s \in S} r(s)a(s).$$

for all $a \in A$ and $b \in B'$. The former inequality implies that $Q \subset \text{cone}(P)$, so we can assume without loss of generality that $q \in P$. By definition, Q must then contain a relatively interior $p \in P$. The latter inequality then implies that $E_p(u(g)) \geq E_p(u(f))$ for all $f \in G$. \square

Proof of Proposition 2. Assume \succsim' is a transitive, c -Archimedean completion of a robust SEU preference relation \succsim on F with representation (u, P) . First note that since \succsim' is a completion of \succsim and by Definition 1, we have

$$x \succsim' y \text{ if and only if } x \succsim y \text{ if and only if } u(x) \geq u(y) \quad (7)$$

for all $x, y \in X$. For all $f \in F$, let $x_f \in \arg \max_{s \in S} u(f(s))$ and $y_f \in \arg \min_{s \in S} u(f(s))$. This is well-defined since S is finite. We then have

$$u(x_f) \geq \max_{p \in P} E_p(u(f)) \geq \min_{p \in P} E_p(u(f)) \geq u(y_f).$$

Since X is convex and u is affine, there then exist $x'_f, y'_f \in \text{conv}(\{x_f, y_f\})$ such that $u(x'_f) = \max_{p \in P} E_p(u(f))$ and $u(y'_f) = \min_{p \in P} E_p(u(f))$. It follows that $x'_f \succsim f \succsim y'_f$ by Definition 1 and, hence, $x'_f \succsim' f \succsim' y'_f$ since \succsim' is a completion of \succsim .

We now show that there exist $\alpha(f) \in [0, 1]$ such that

$$f \sim' \alpha(f)y'_f + (1 - \alpha(f))x'_f.$$

If $f \sim' x'_f$ or $f \sim' y'_f$ then we are done, so assume $x'_f \succ' f \succ' y'_f$. By (7), we then have $u(x'_f) > u(y'_f)$. Let

$$\begin{aligned} L &= \{\lambda \in [0, 1] : \lambda y'_f + (1 - \lambda)x'_f \succsim' f\}, \\ M &= \{\mu \in [0, 1] : f \succsim' \mu y'_f + (1 - \mu)x'_f\}. \end{aligned}$$

We then have $L \cup M = [0, 1]$ since \succsim' is complete. Moreover, for all $\lambda \in L$ and $\mu \in M$, we have $\lambda y'_f + (1 - \lambda)x'_f \succsim' \mu y'_f + (1 - \mu)x'_f$ since \succsim' is transitive and, hence, $u(\lambda y'_f + (1 - \lambda)x'_f) \geq u(\mu y'_f + (1 - \mu)x'_f)$ by (7). Since u is affine and $u(x'_f) > u(y'_f)$, this is only possible if $\lambda \leq \mu$. It follows that $\sup L = \inf M$. Finally, L and M are closed since \succsim' is c-Archimedean and, hence, $\sup L = \max L$ and $\inf M = \min M$. Hence, letting $\alpha(f) = \max L = \min M$ and $z_f = \alpha(f)y'_f + (1 - \alpha(f))x'_f$, we have $f \sim' z_f$.

Finally, let $V(f) = u(z_f)$. Since u is affine, we then have

$$V(f) = \alpha(f)u(y'_f) + (1 - \alpha(f))u(x'_f) = \alpha(f) \min_{p \in P} E_p u(f) + (1 - \alpha(f)) \max_{p \in P} E_p(u(f)).$$

Moreover, since \succsim' is transitive and by (7), we have

$$f \succsim' g \text{ if and only if } z_f \succsim' z_g \text{ if and only if } V(f) \geq V(g)$$

for all acts $f, g \in F$, which completes the proof. \square

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